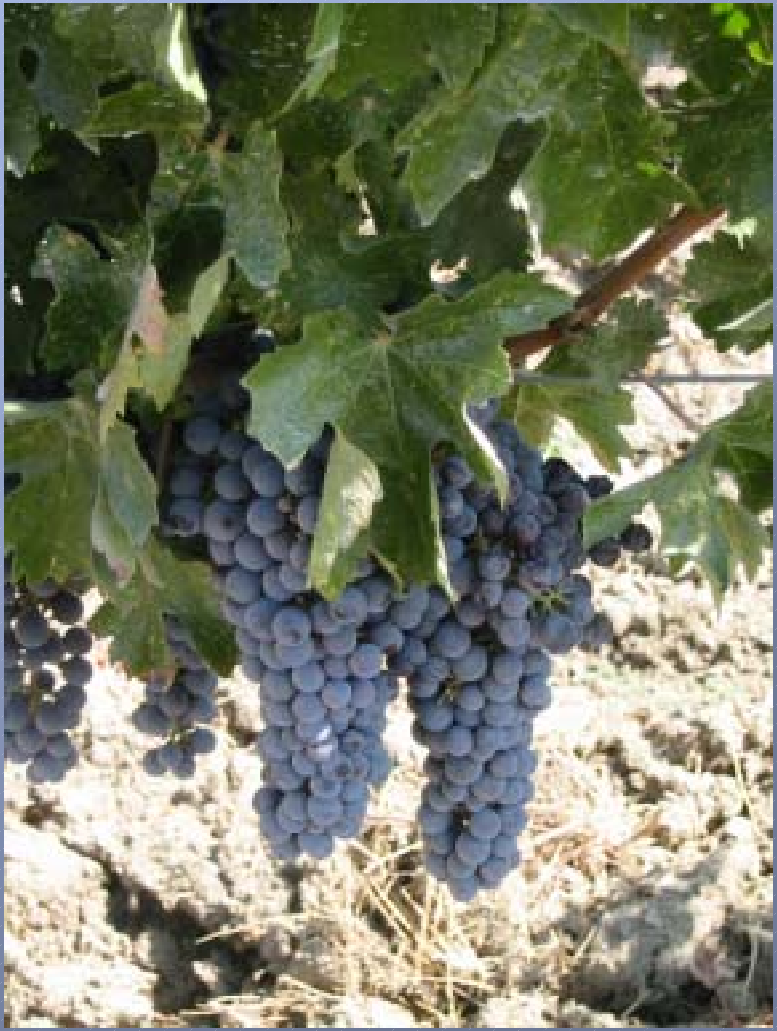
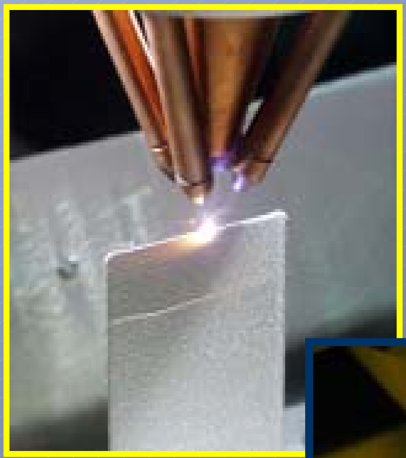
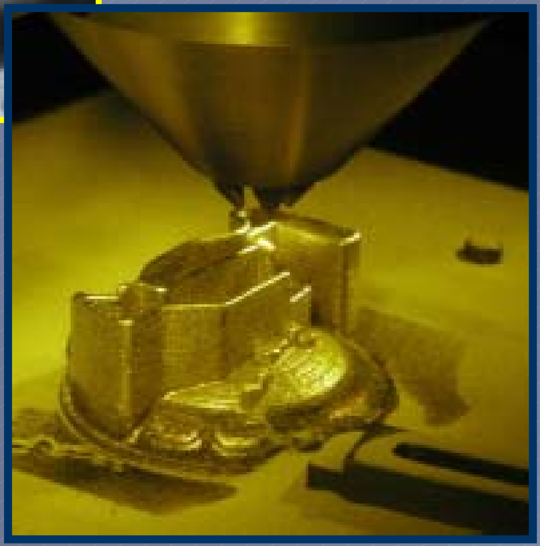


Model Based Materials Processing for In-Space Fabrication





John E. Smugeresky[1],
David M. Keicher[2]
and
Richard Grylls[2]

[1]Sandia National Laboratories,
Livermore, CA 94551-0969
[2]Optomec Design Company, Albuquerque, NM 87123

In-Space Fabrication and Repair Research:
An Industry - NASA - Academia Technical Forum
July 8-10, 2003

* Laser Engineered Net Shaping (LENS™), is a registered trademark of Sandia National Laboratories

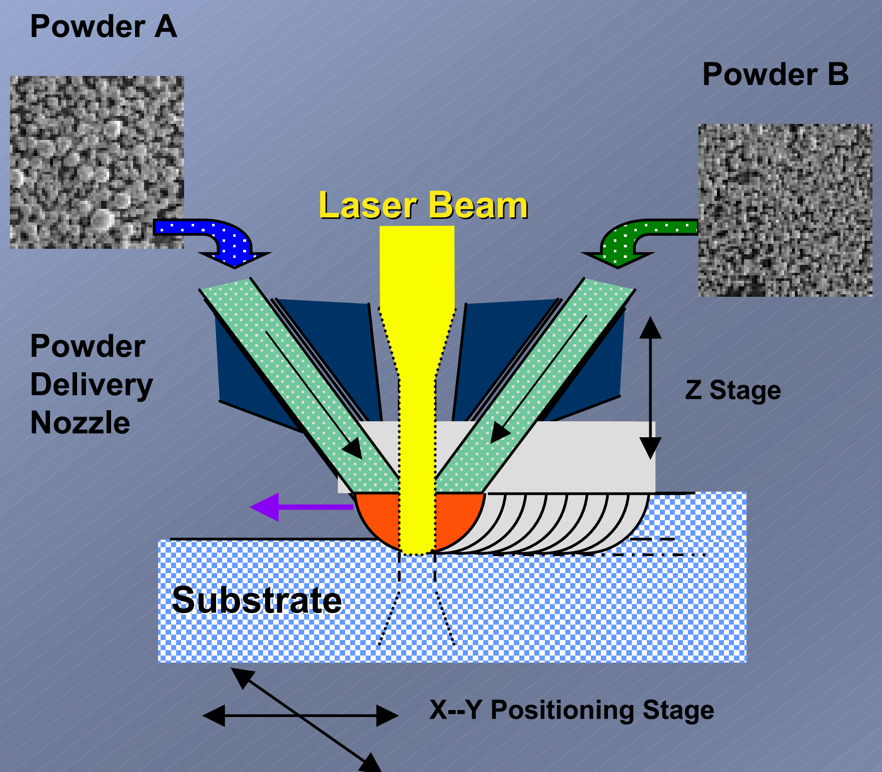
Work Performed under a CRADA supported by an Optomec NSF Project and by the U. S. Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Topics

- Laser Assisted Materials Processing
  - Based on Physical Metallurgy Principles
- Microstructure Via Solidification Processing
  - Materials, Microstructure, and Property Relations
- Features Related to In-Space Fabrication
- Potential of LENS™ for Pseudo-Universal In-Space Materials Fabrication

Model Based Metal Forming (LENS™)

Laser Powder Deposition



1. Laser Beam Scans a Substrate While Powdered Materials are simultaneously delivered to the Laser focal point

2. Model defines scanning patterns and where material is wanted, turns on Laser, and powder particles are captured, adding material to the substrate

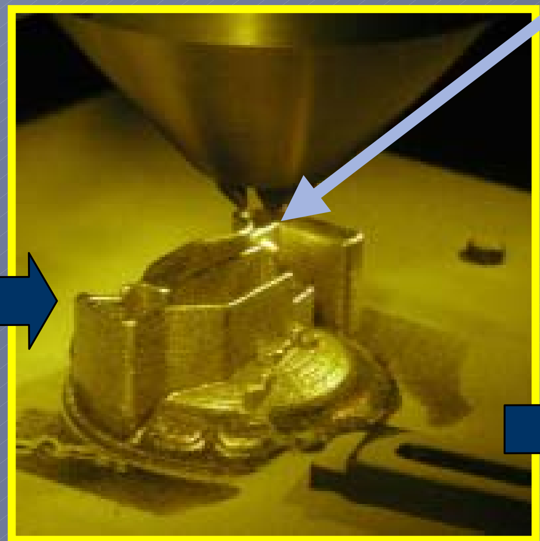
3. Small Molten Pool Is Formed and Quickly Cools, Leaving Behind a Narrow Deposited Solid Line of Material

Laser Engineered Net Shaping (LENS™)

Electronically Designed Model of Housing

- **CAD Solid Model**
- **Electronically Segmented Into Horizontal Layers**
- **Scanning Patterns Created**

LENS™ Additive Forming Process



- **Laser Powder Deposition**
- **Forms Part Line by Line**
- **Layer by Layer**
- **Without Tooling**

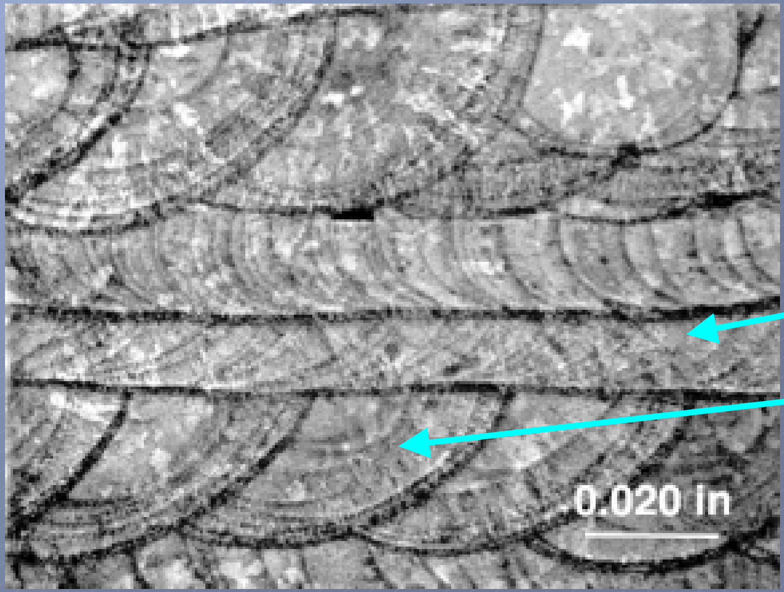
Finished Functional Housing

Laser Engineered Net Shaping (LENS™) Is an Additive Forming Process for Structural Materials

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

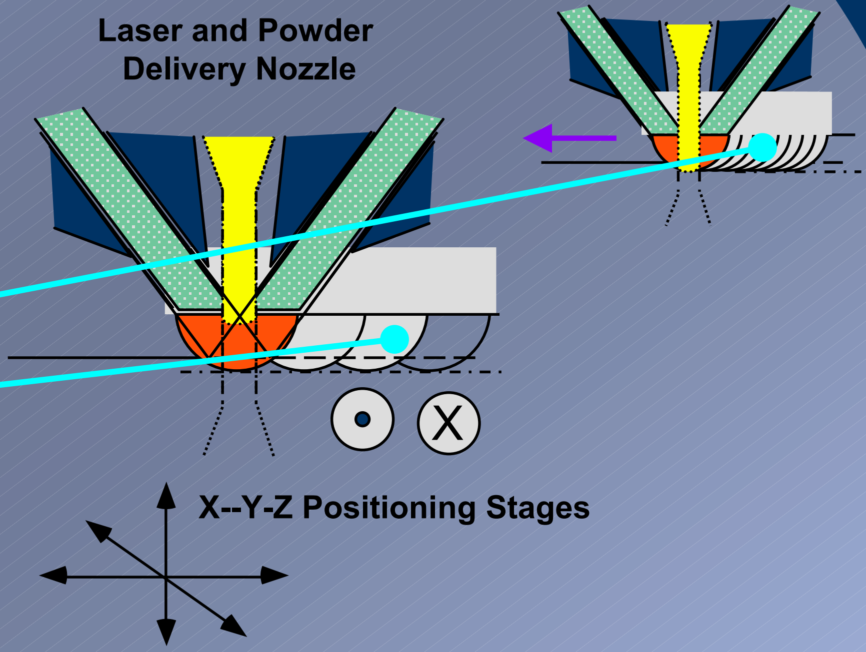
Cross Section of Deposited Material Shows Solidification Microstructures



316 SS Highest Strength

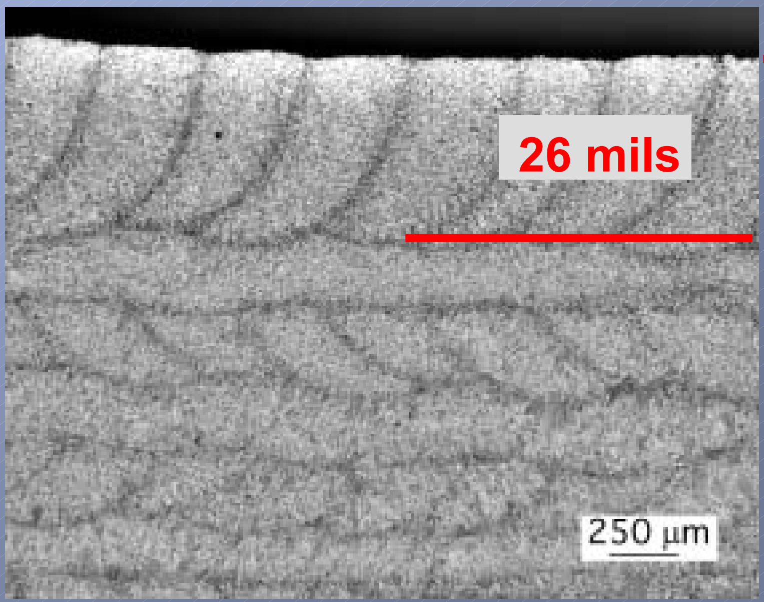
Sample 010996-V

Ultimate Tensile Strength	115 KSI
Yield Tensile Strength	85 KSI
Total Elongation in 1 inch	30 pct

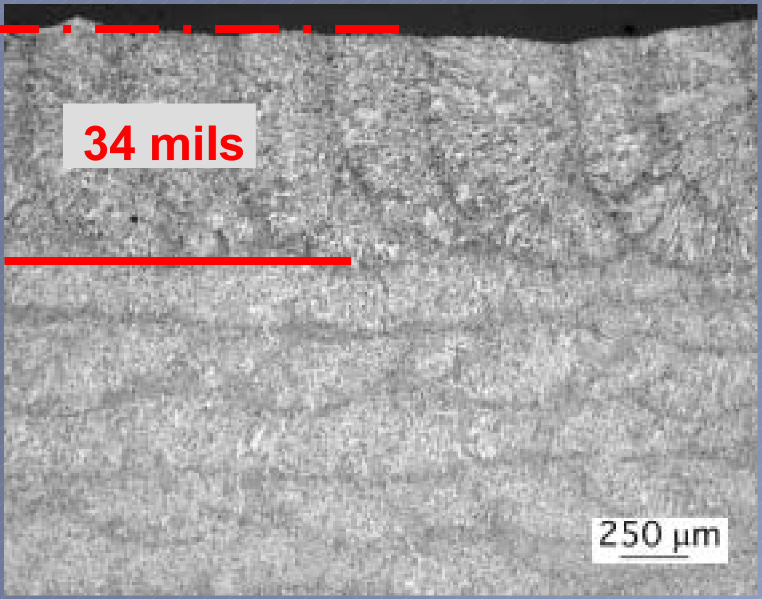


Travel Speeds	**≤ 40 ipm**
Molten Pool Width	**≤ 0.040 in.**

Deposit Detail Depends on Processing Conditions

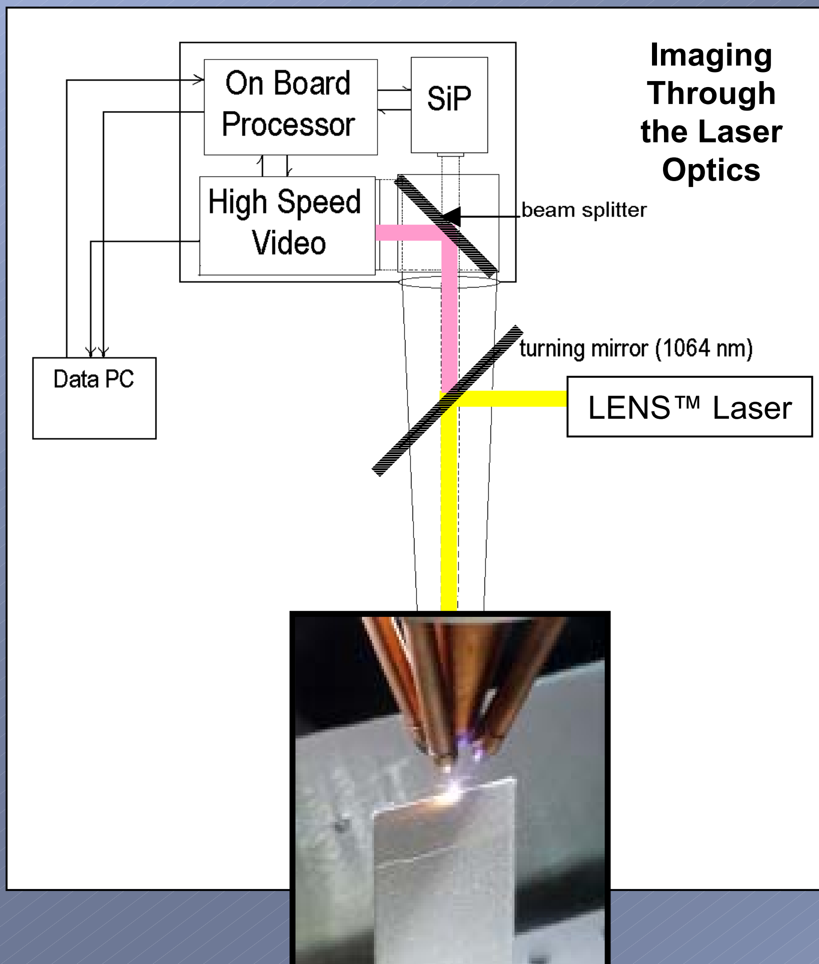


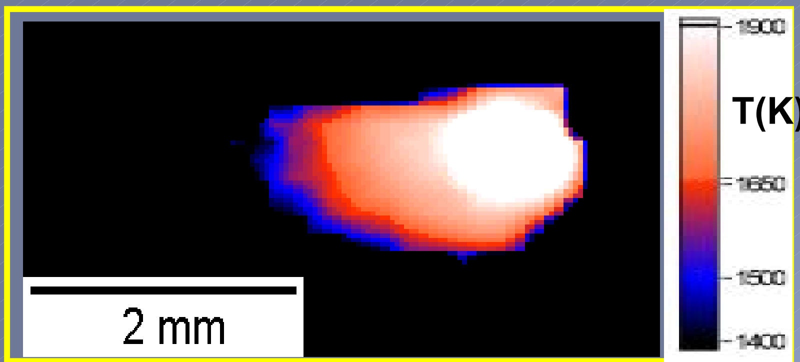
FR5
Ratio = 600
Power = 300 W,
Speed = 30 ipm
PFR = 30



FR3
Ratio = 600
Power = 300 W,
Speed = 30 ipm
PFR = 20

Microstructure Control based on Temperature Distribution and Kinetic Data from High Speed Imaging of Deposition



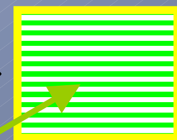


“Image” of Melt Pool
As Viewed Through Laser Optics

From Hofmeister, et. al

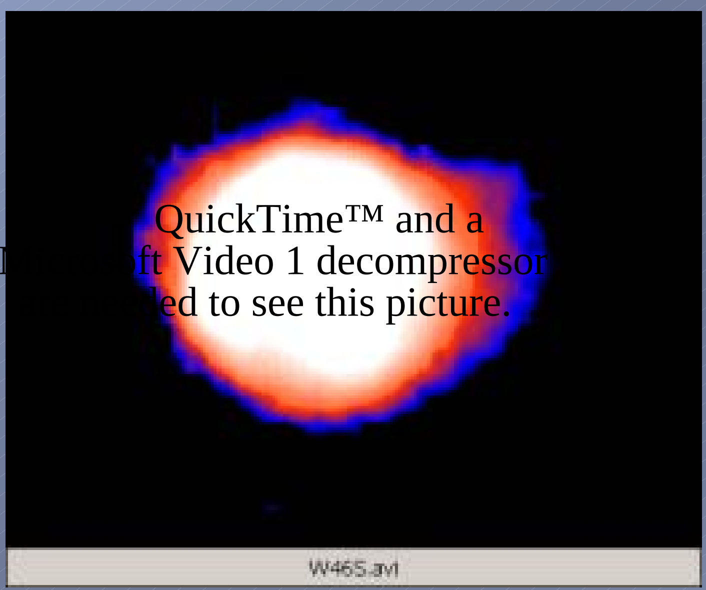
Movies Show Differences in Melt Pool Depending on Processing Conditions

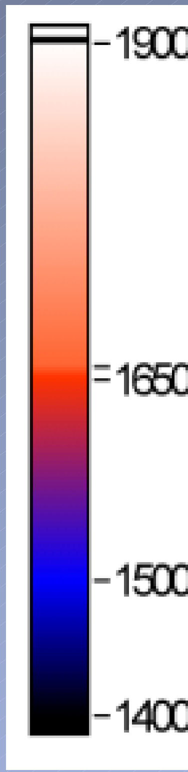
Cube Build Pattern
0.5 X 0.5 Inch



Fill

Border





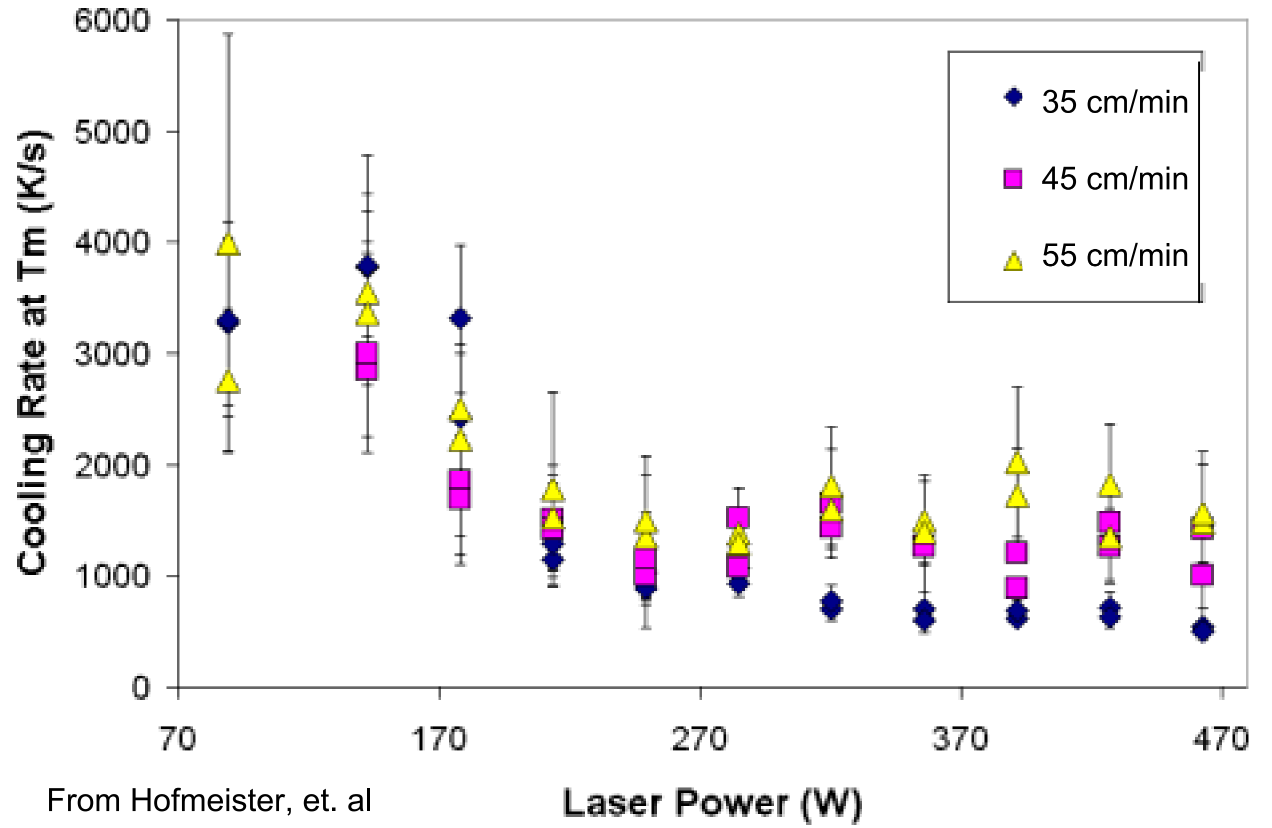
"Fill"

H13 Tool Steel

"Border"

From Hofmeister, et. al

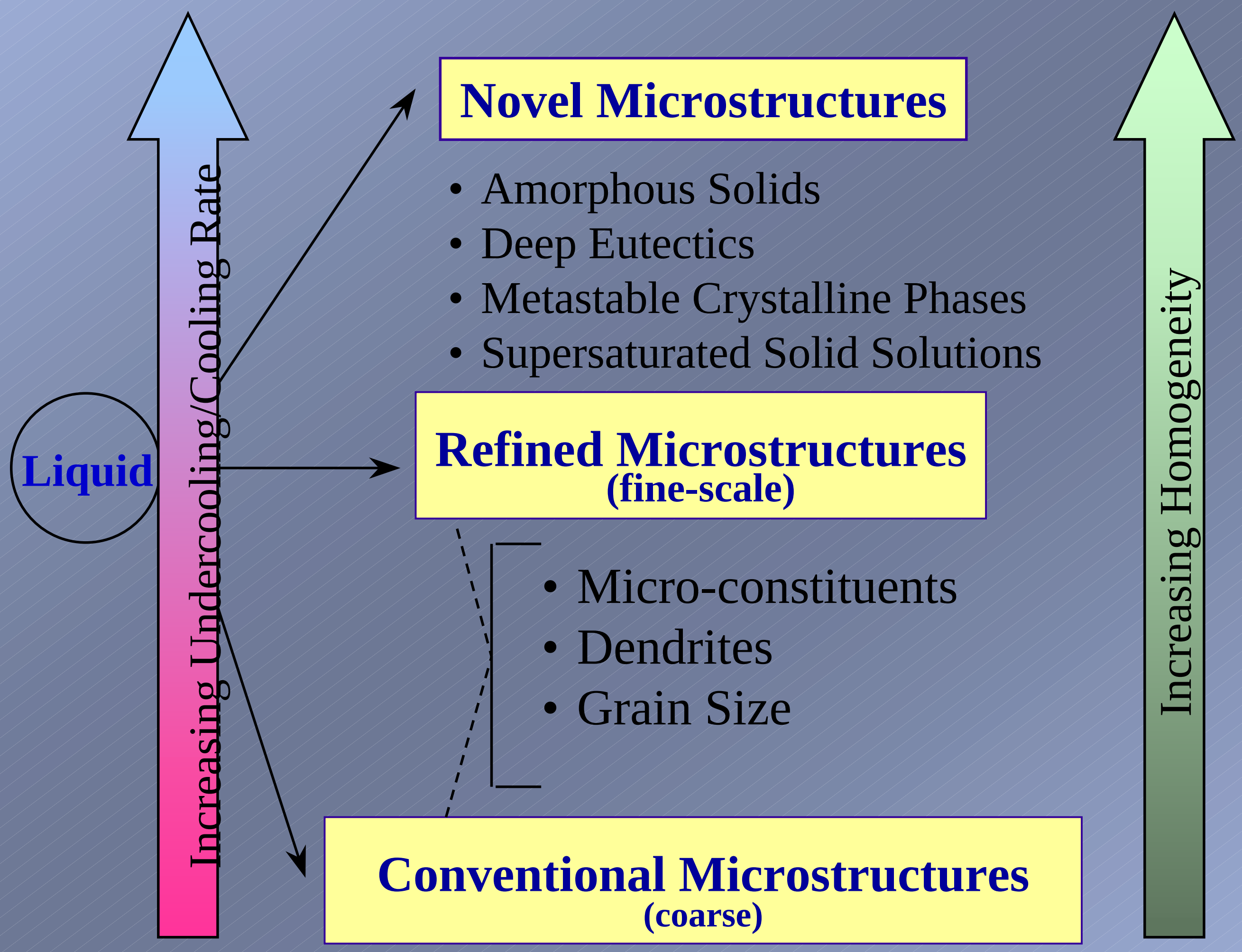
Cooling Rate at Solid Liquid Interface of Line Builds Suggests Rapid Solidification Deposition Conditions



From Hofmeister, et. al

The cooling rates were calculated from image data frame by frame, and the standard deviations of these measurements for each file are shown in the error bars.

The Principles of Rapid Solidification and Materials Science can be used to Select Microstructural Features For Enhanced Properties



Topics

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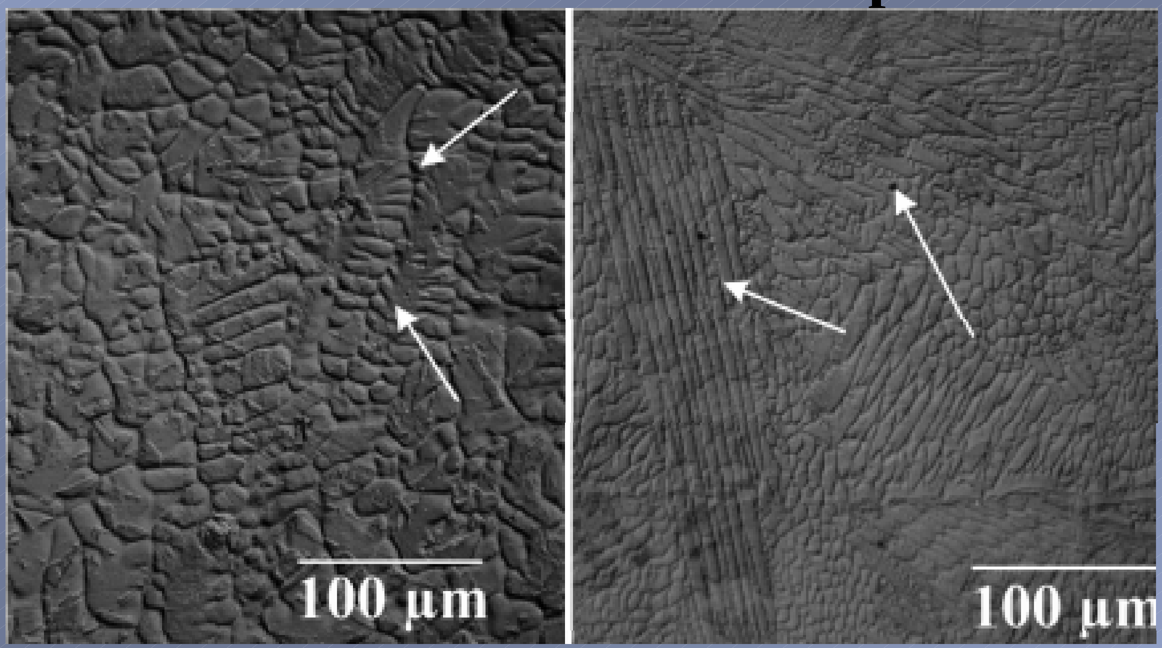
By Varying the Cooling Rate, Microstructure Features Can Be Selected

For Fe-25wt.%Ni: $\lambda_2 = 60\varepsilon^{-0.32}$

rod | plate

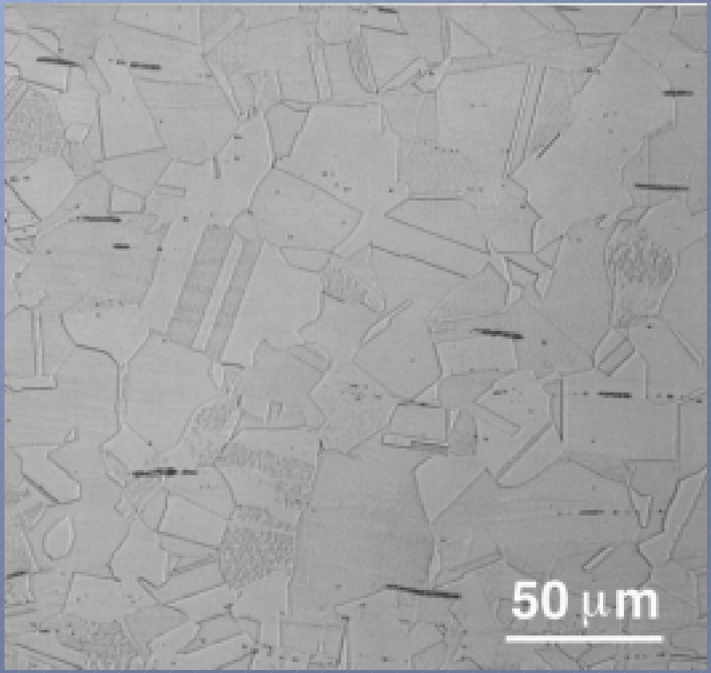


$\lambda_2 \approx 12.5\mu m$ | $\lambda_2 \approx 3\mu m$

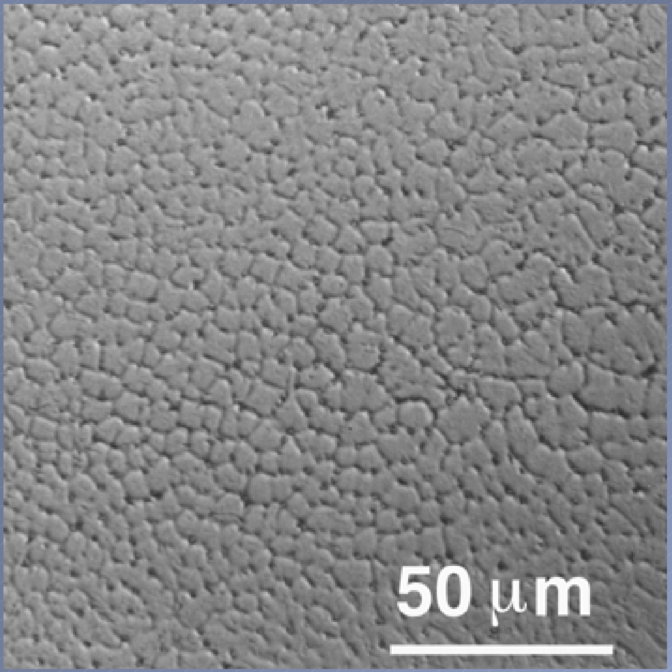
$\varepsilon \approx 150 K/s$ | $\varepsilon \approx 1x10^4 K/s$

From Thoma, et. al

Grain/Cell Refinement and Absence of Long Sulfide Stringers Observed in 316 Stainless Steel



Conventional Process
(grain size = 50 μm)
ASTM 6



LENS™ Process
(grain/Cell size = 5 μm)
ASTM 13

Optomec Sandia National Laboratories

Mechanical Properties of LENS™ Processed Materials Exceed Those of Wrought Annealed Barstock

	LENS™ IN 625	Wrought IN 625	LENS™ 316 SS	Wrought 316 SS
UTS (KSI)	135	121	115	85
YTS (KSI)	92	58	65 ←	35
et (%)	38	37	51 ←	50

Strength is Enhanced with No Loss of Ductility

Strengthening Consistent with Hall-Petch Grain Size Relationship

Conventional Processing $d_1 = 50\ \mu m$

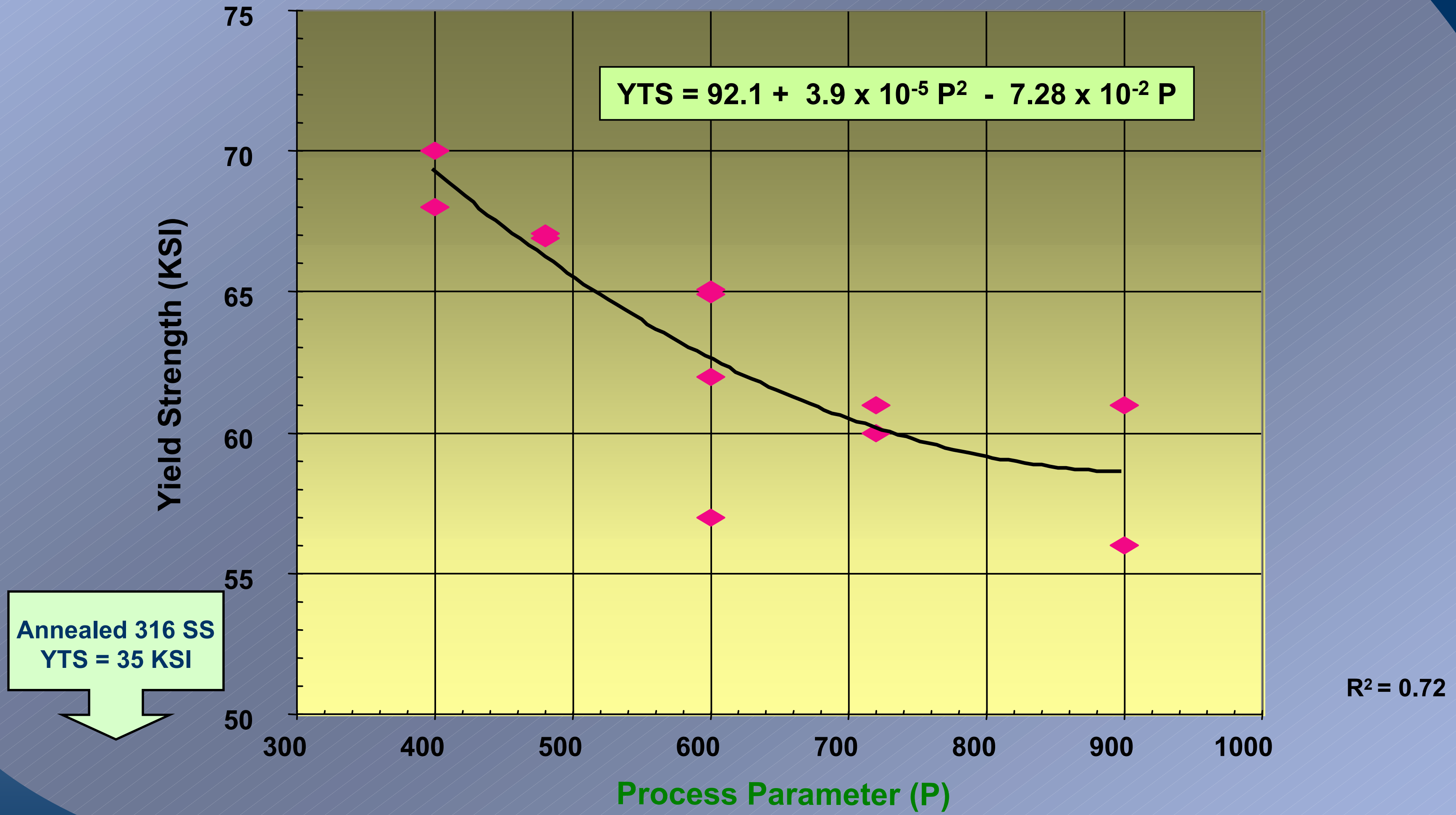
LENS™ Processing $d_2 = 5\ \mu m$

Hall-Petch Yield Strength (σ) $= K\,(d)^{-1/2}$

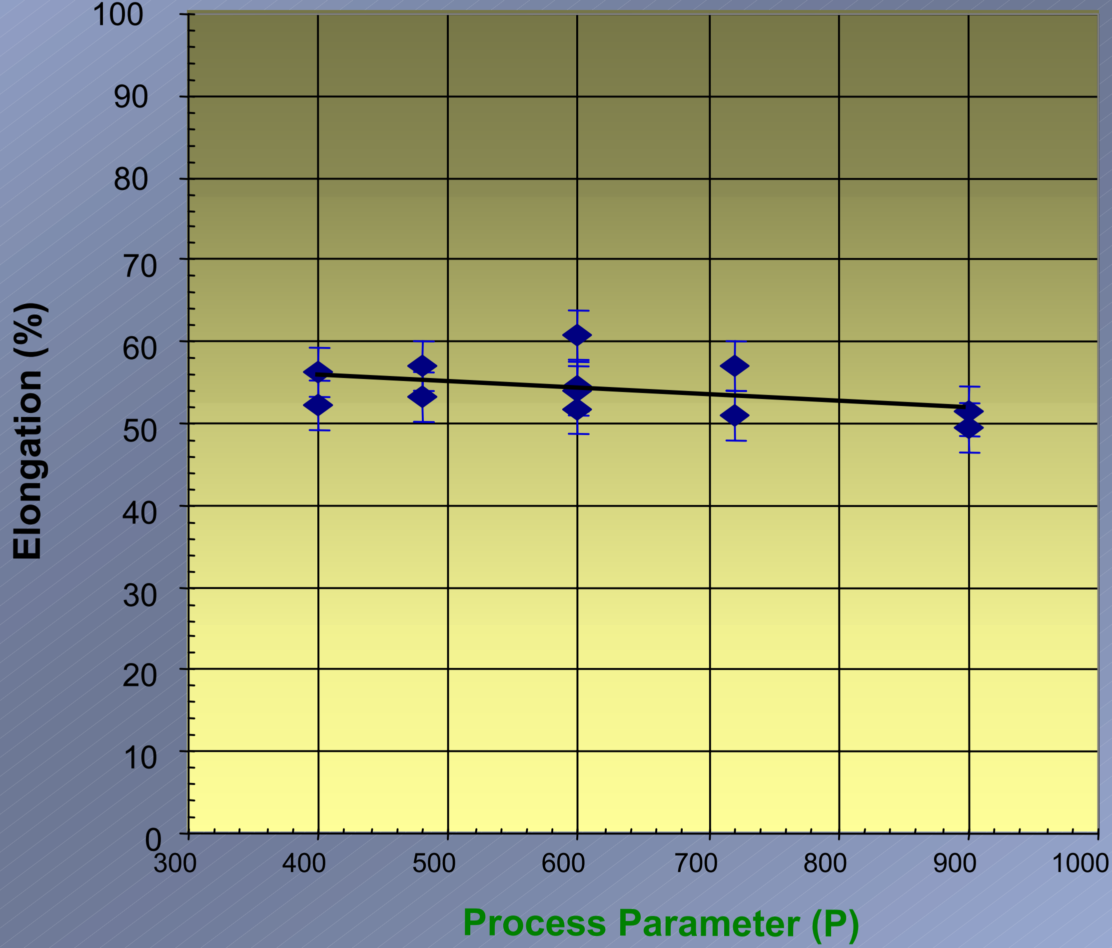
$$\frac{(\sigma_2)}{(\sigma_1)} = \frac{(d_1)^{1/2}}{(d_2)^{1/2}}$$

$$\frac{(\sigma_2)}{(\sigma_1)} = (10)^{1/2} \approx \text{3 fold increase}$$

Yield Stress Can Be Selected, *by Process Parameter P*, to More Than Twice That of Annealed 316 SS



Ductility Appears Independent of Process Parameter P Over the Range That Can Double the Strength for 316 SS



AVG. = 54.1±3.2 %

Can Use Processing Conditions to Vary Cooling Rate and Control Grain Size

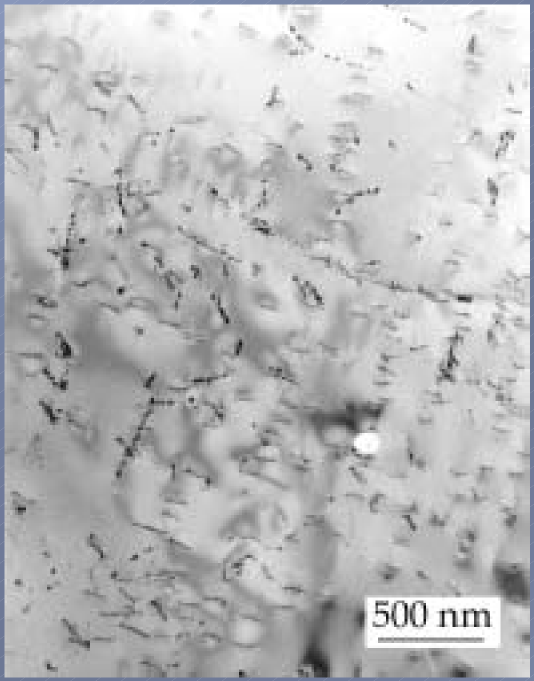
Lower Cooling Rate:
Largest Grain Size
FR4

Higher Cooling Rate
Smallest Grain Size
FR7

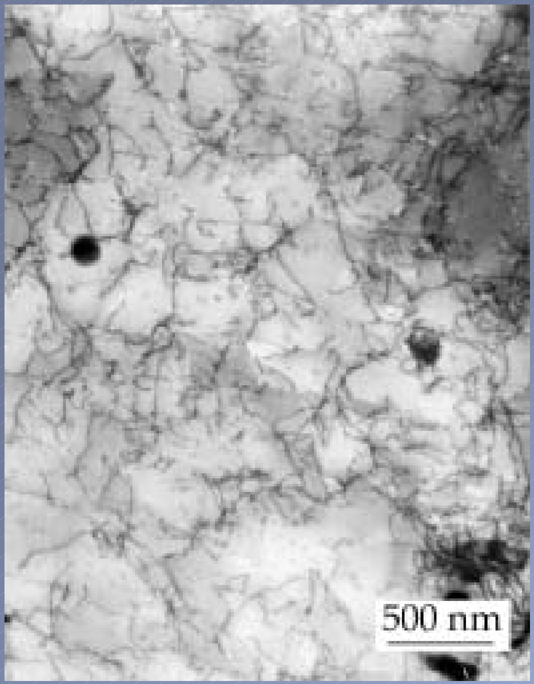
Faster Cooling Rate Gives
Smaller Grain Size and Should Provide Higher Strength.

Dislocation Density is Similar to Annealed Condition But Does Vary with Process Conditions

Typical Dislocation Densities
g = (111)



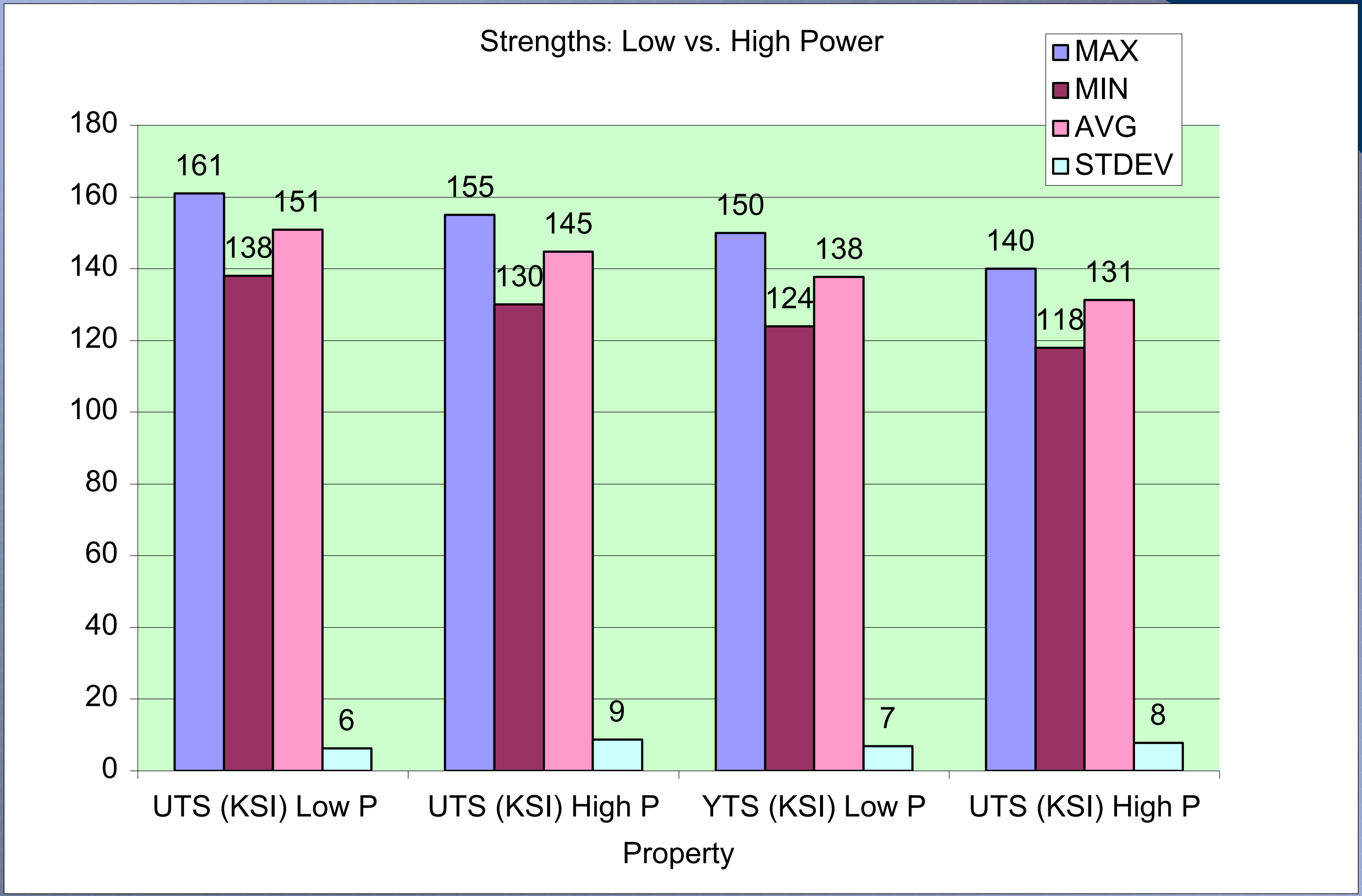
Lower Cooling Rate
FR4



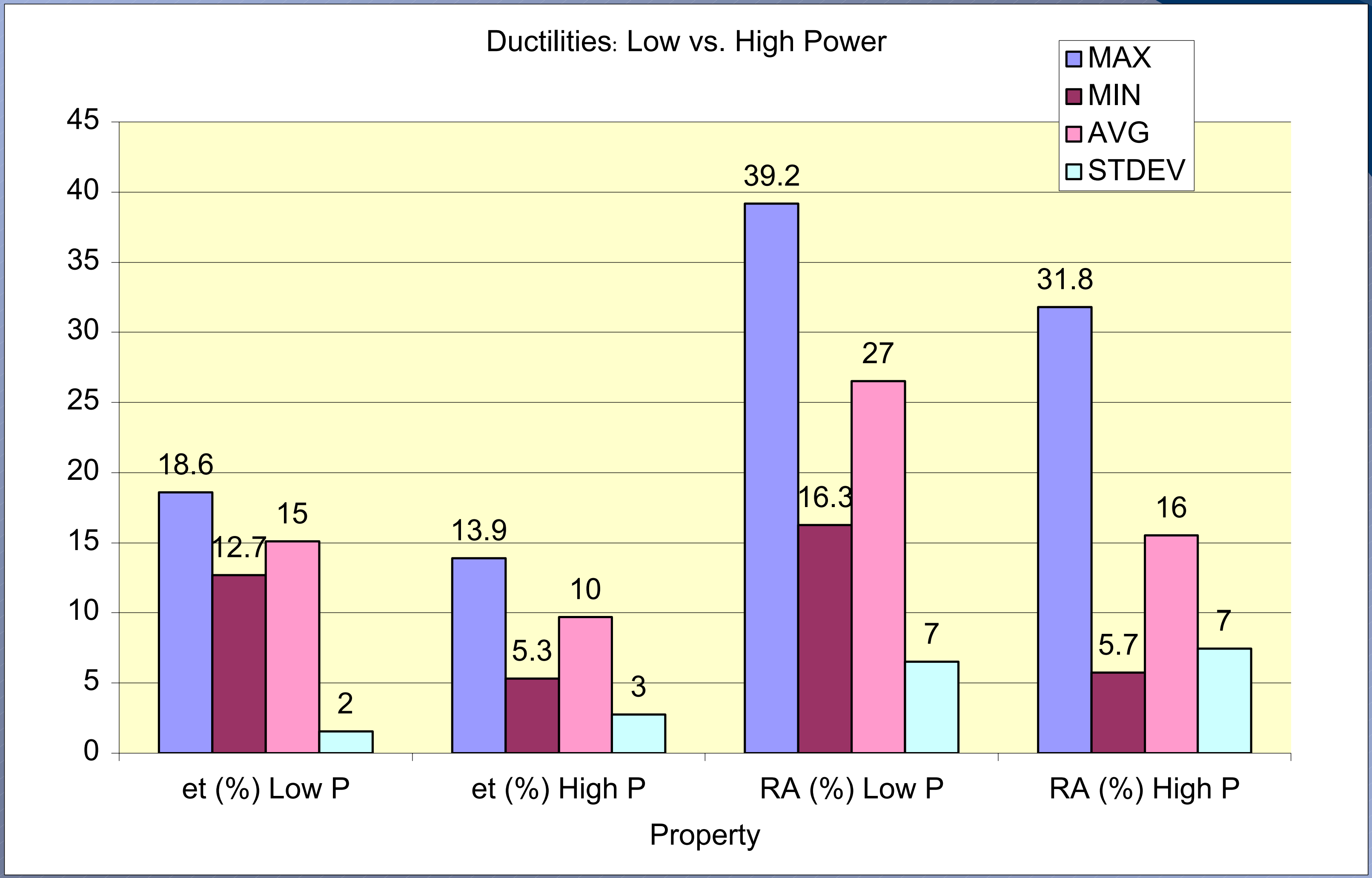
Higher Cooling Rate
FR7

A Variety of Metals Have Been Processed by LENS™

- Stainless steels: 316, 304L, and 309S
- Nickel alloys: 718, 625, and 690
- Tool steel alloys
  - (H-13, Nu-Die EZ, MM-10, CPM-10)
- Titanium (6Al-4V)
- Limited Amounts of:
  - Aluminum
  - Titanium Aluminide (γ)
  - Tungsten
  - Cermets
  - Magnetic alloys

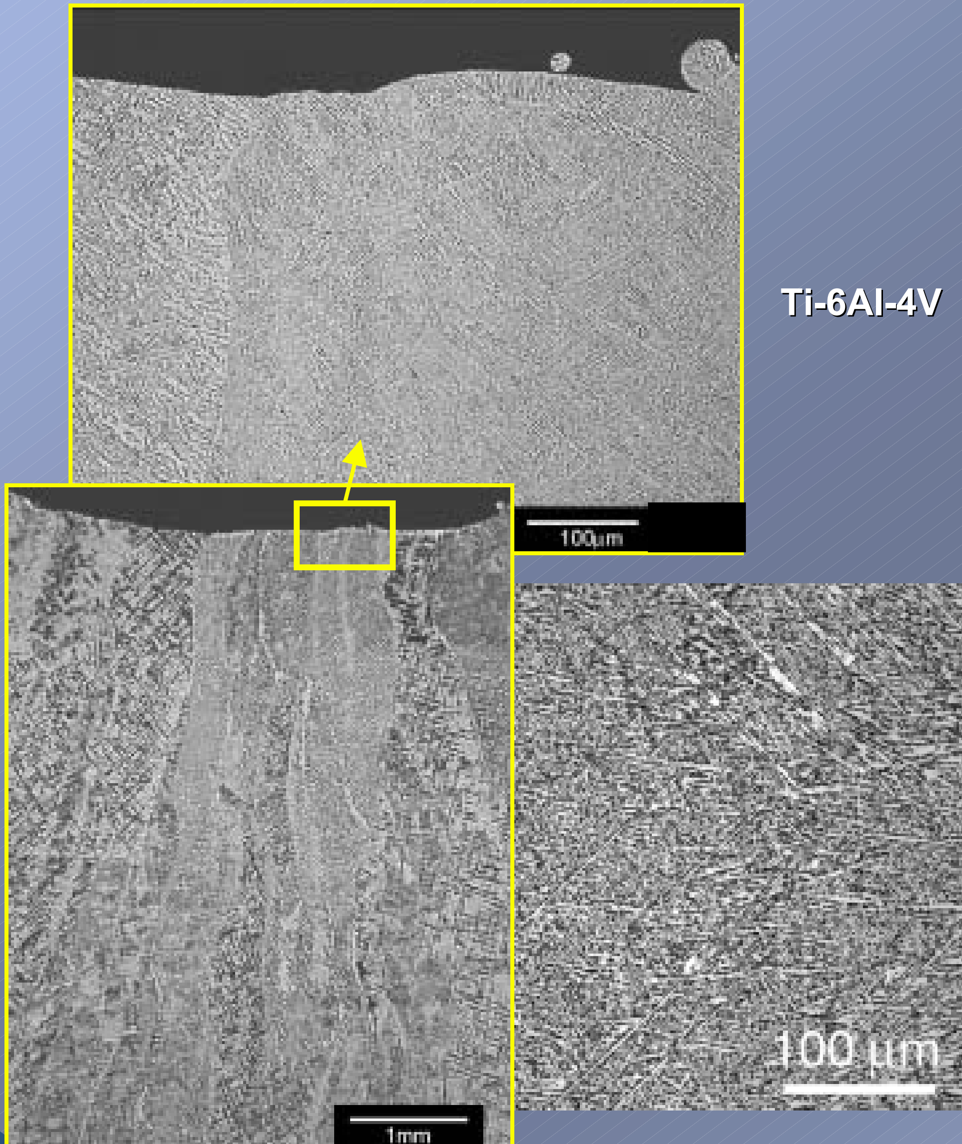

Strengths: Low vs. High Power
MAX
MIN
AVG
STDEV
180
160
140
120
100
80
60
40
20
0
161
138
151
6
155
130
145
9
150
124
138
7
140
118
131
8
UTS (KSI) Low P
UTS (KSI) High P
YTS (KSI) Low P
UTS (KSI) High P
Property

D

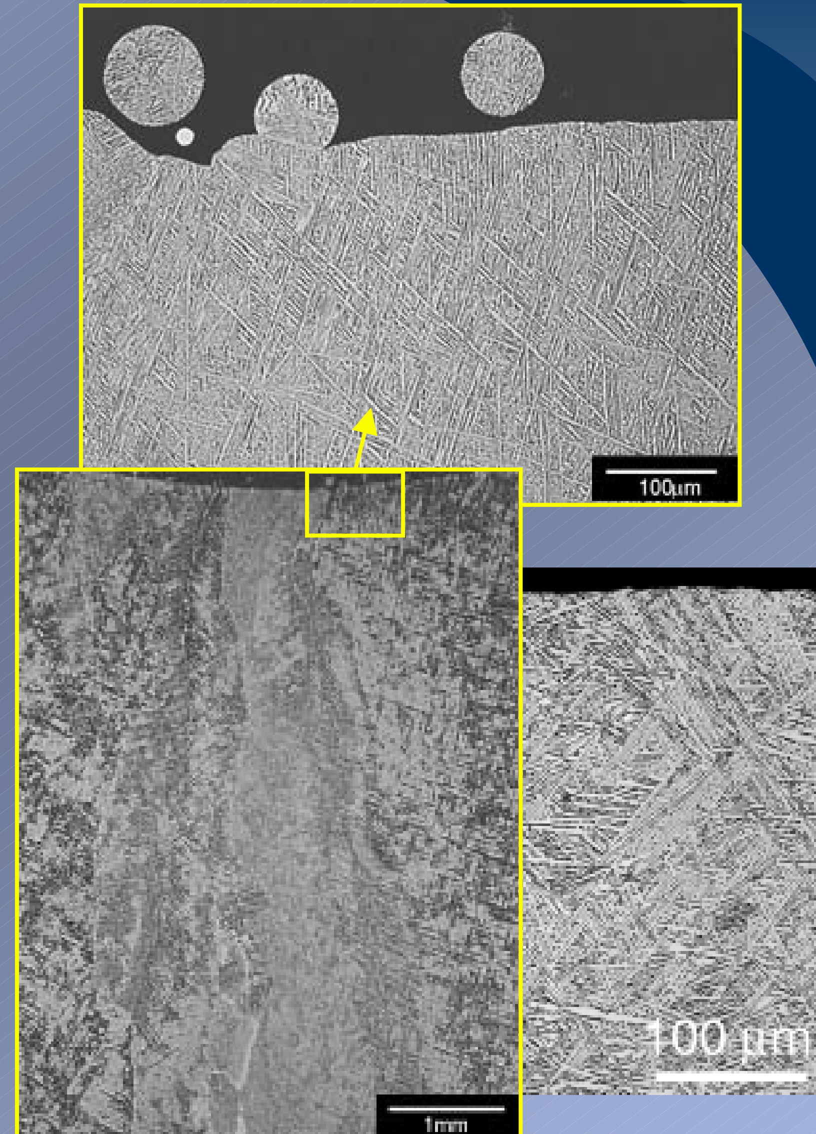


Ductilities: Low vs. High Power
MAX
MIN
AVG
STDEV
45
40
35
30
25
20
15
10
5
0
18.6
12.7
15
2
13.9
5.3
10
3
39.2
16.3
27
7
31.8
5.7
16
7
et (%) Low P
et (%) High P
RA (%) Low P
RA (%) High P
Property

Columnar Microstructure Suggests Epitaxial Growth Across Layer Boundaries



Ti-6Al-4V

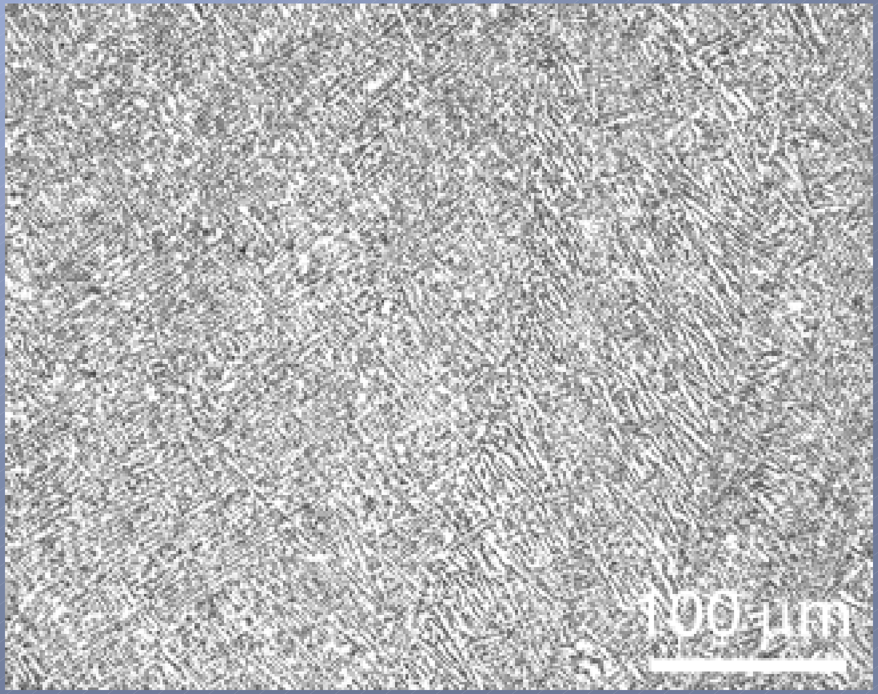


RGT-21,Top,500X_3.47.jpg

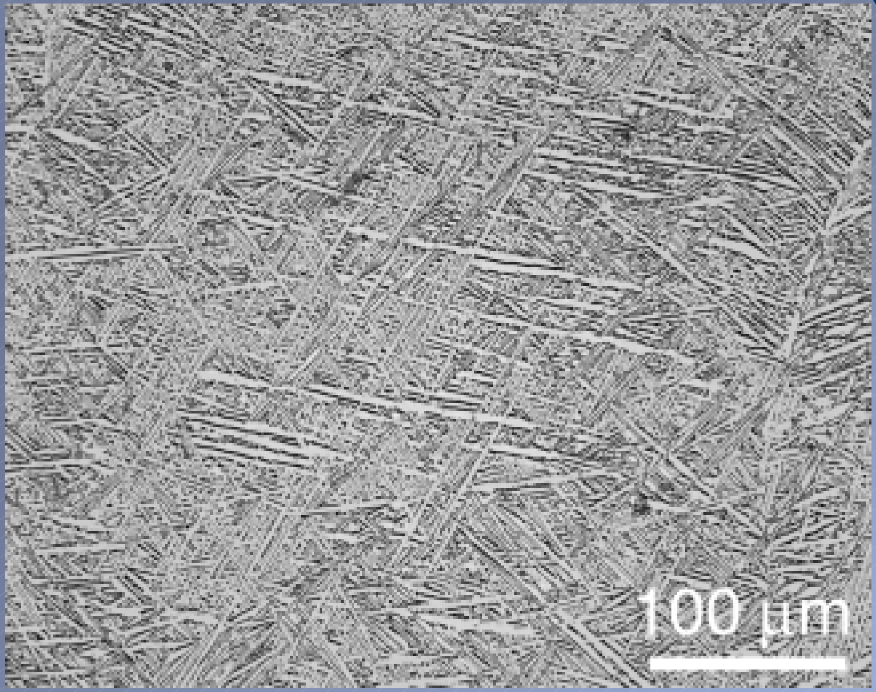
RGT_51

Lower Power Provides Finer Structure

Ti-6Al-4V



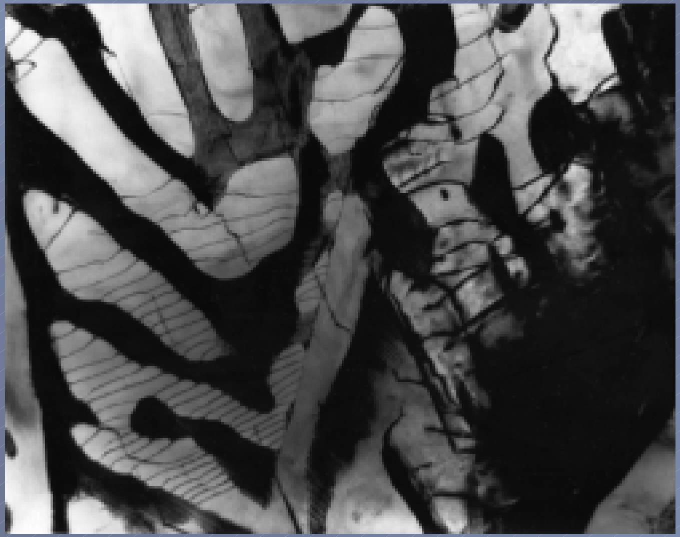
Lower Power



Higher Power

TEM Microstructures

13 microns

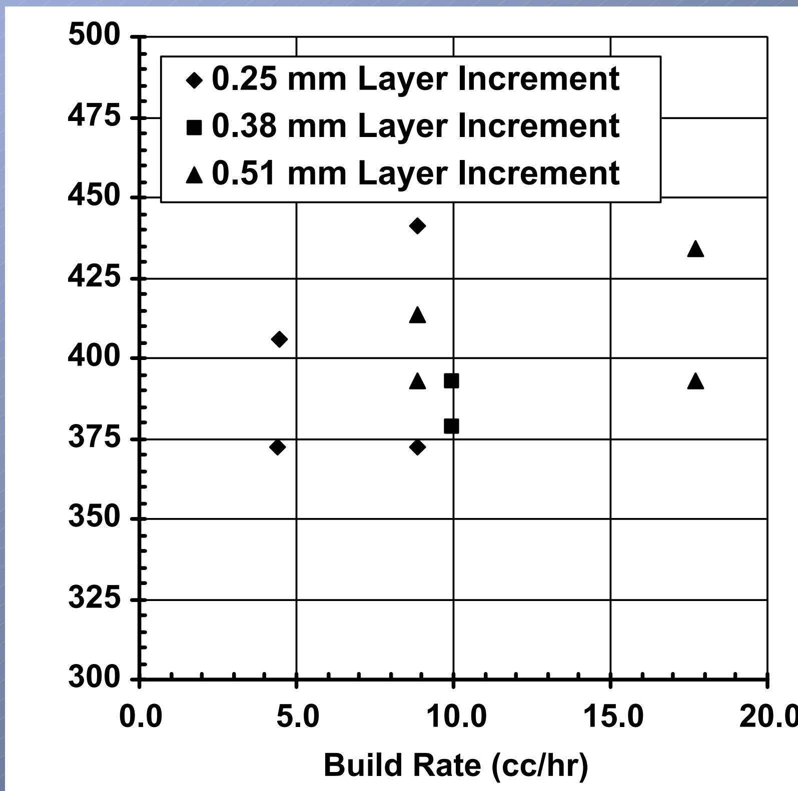


1.8 microns

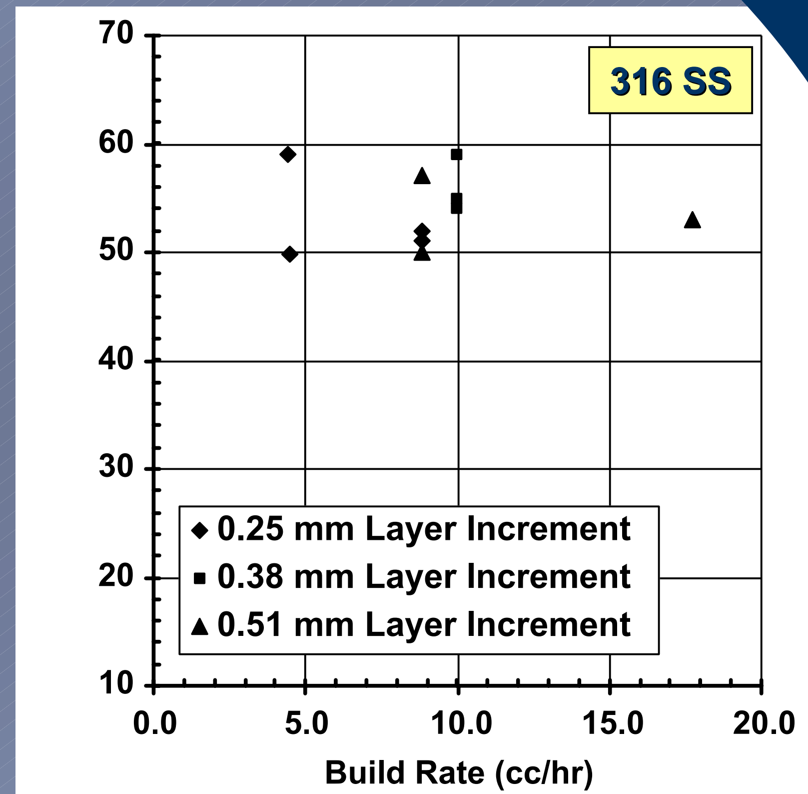
- Acicular alpha (hcp phase; light phase)
- Intergranular beta (bcc phase; dark phase) titanium.
- The acicular a transformed from the beta phase during cooling from above the beta transus (883 °C).
- The alpha phase forms by nucleation and growth on crystallographic planes of the prior beta.
- Leads to packets or colonies of alpha aligned in the same orientation. Multiple orientations of alpha yield the basket-like appearance observed in this microstructure.

From C. A. Drewien

Enhanced Mechanical Properties Can Be Maintained at Build Rates up to 18 cc/hr*



Yield Strength is weakly dependent on build rates investigated



Ductility (pct elongation) appears independent of build rate with one exception

* 1.0 in^3/hr)

For Ti-6Al-4V Build Rates up to 180 cc/hr* Have Recently Been Achieved

Properties After HIPping:

Ultimate	133 KSI
Tensile	118 KSI
Elongation	14 %
RA	37 %

Other Data for Comparison

Sample ID	UTS (KSI)	YTS (KSI)	et (%)
plate, trans.	151.7	146.3	16.4
plate, align	154.7	148.0	16.0
LENS-SNL	145.0	135.0	15.0
LENS-Optomec	170.0	155.0	11.0
Specification	140.0	120.0	10.0

* 10.0 in^3/hr)

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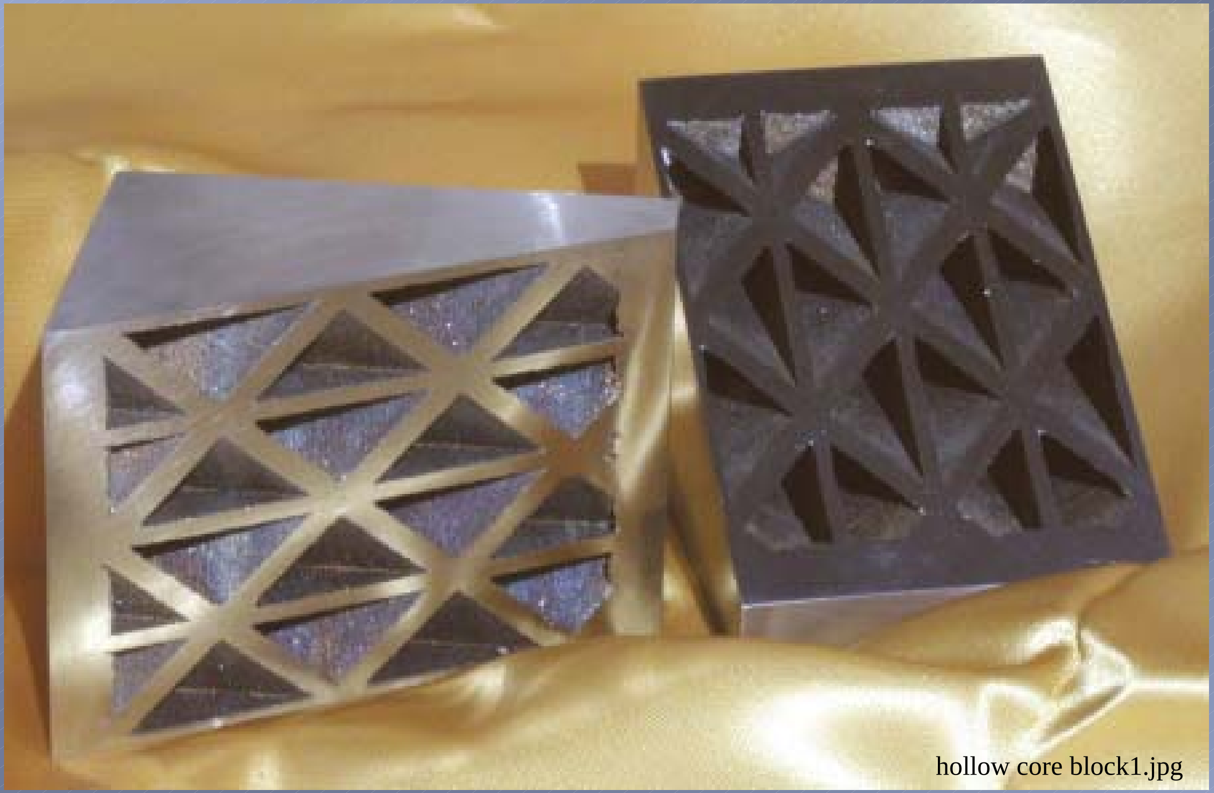
Hollow Core Block Exhibiting Overhang Capability

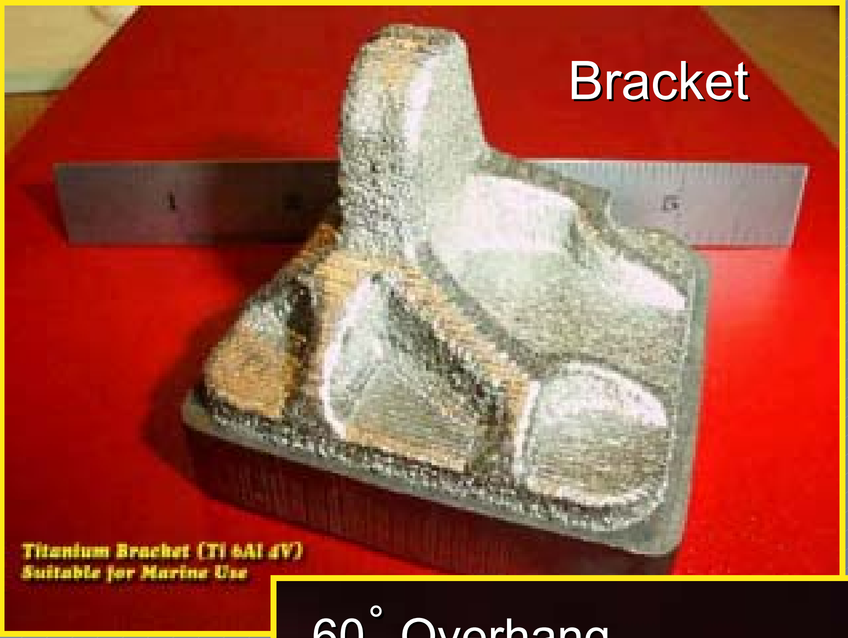


Allows Building of Hollow Features
In Tooling for Plastic Injection Molding or Weight Reduction

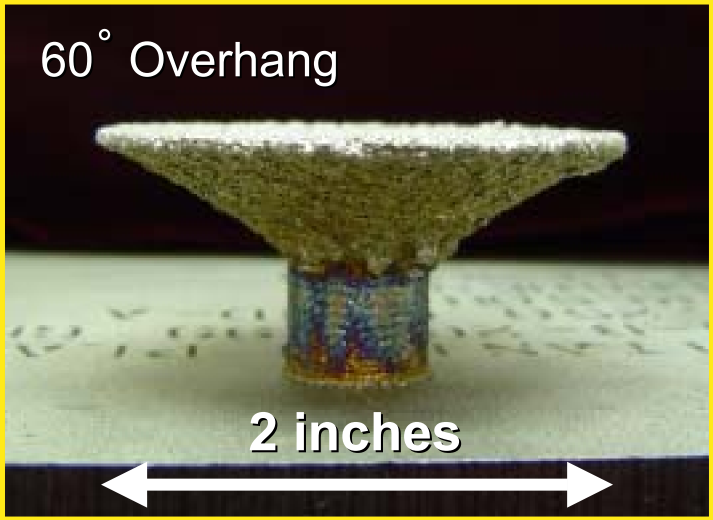
Optomec

Sandia National Laboratories

LENS Processed Titanium (Ti-6Al-4V) Component Feature Development

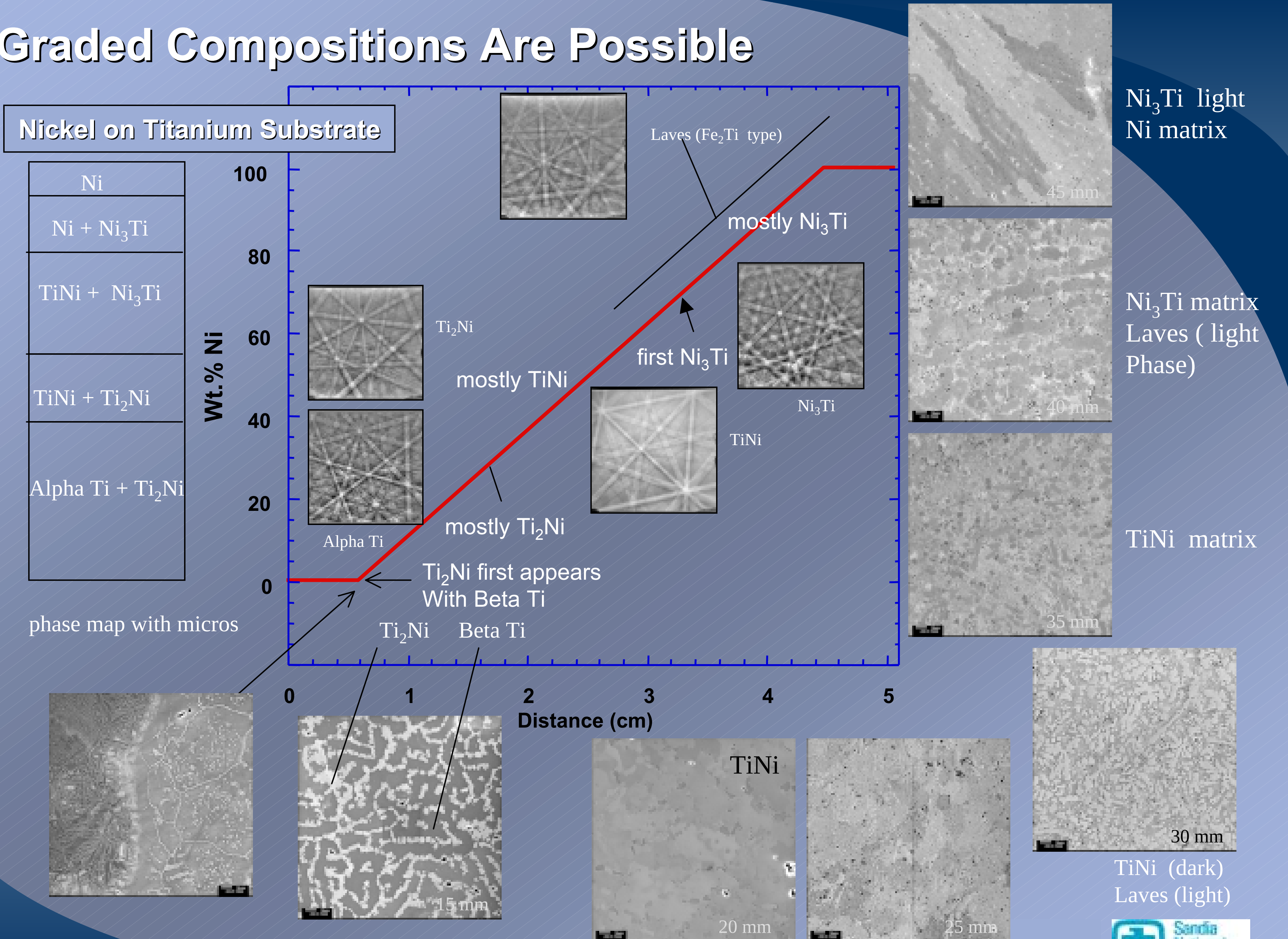


Achieving 90° Overhang
is Another Driver For Process Improvement



Started at 17° from Vertical Overhang

Graded Compositions Are Possible



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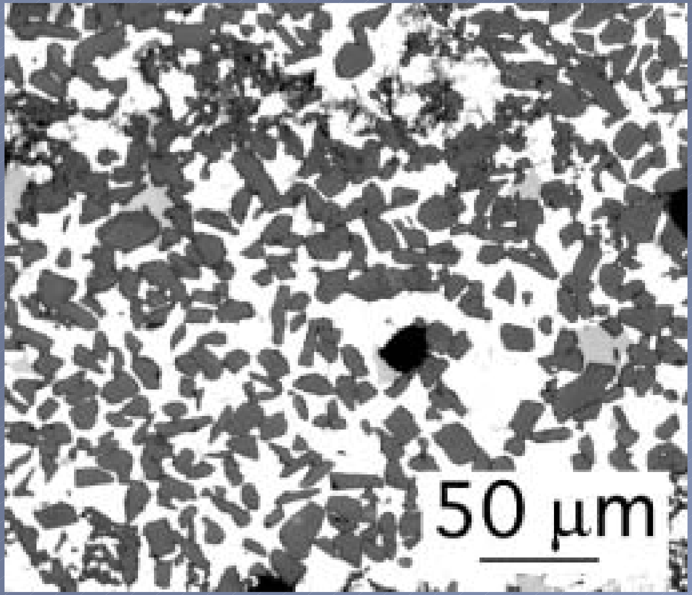
LENS™ Processed Aluminum Is of Interest to DoD for Sensor and Thermal Management Applications



1.5 in.

For Aluminum Alloys:
Have Demonstrated Ability
to Make Hollow cylinders

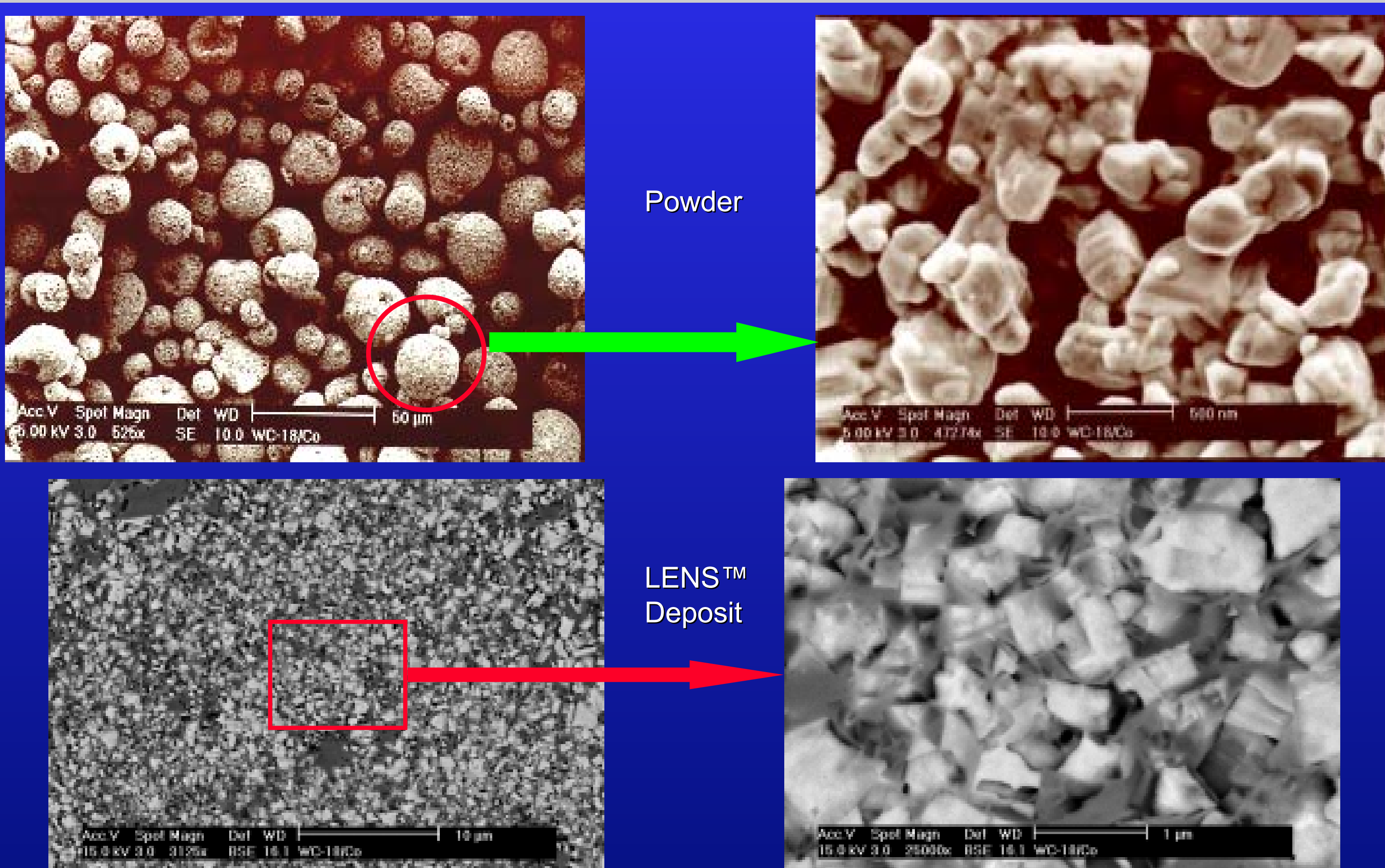
For Metal Matrix Composites:
Have Achieved a More Uniform and
Larger Volume Fraction Particulate
Than Alternate Processing
Technologies

Using LENS^{TM} Process to Fabricate Nano-Crystalline Hard Materials

- Tungsten carbide (WC) has exceptional hardness and wear/corrosion resistance.
- Introduction of Co as a binder (in a range of 3% to 30%) can improve the overall toughness and avoid brittle fracture of the wear resistant WC phase
- Hardness Is Increased by Decreasing grain/particle size
- But decomposition of WC into brittle phases (into W_2C, or $Co_xW_yC_z$) can form in Spray deposited material causing sliding and abrasive wear

- With WC-18 wt. % Co powder, nano-crystalline LENS^{TM} deposited microstructure with increased thermal stability of WC has been realized
- Characteristic LENS^{TM} processing conditions (Short high-temperature duration time and nearly oxygen free environment) provides the more desirable microstructure feature

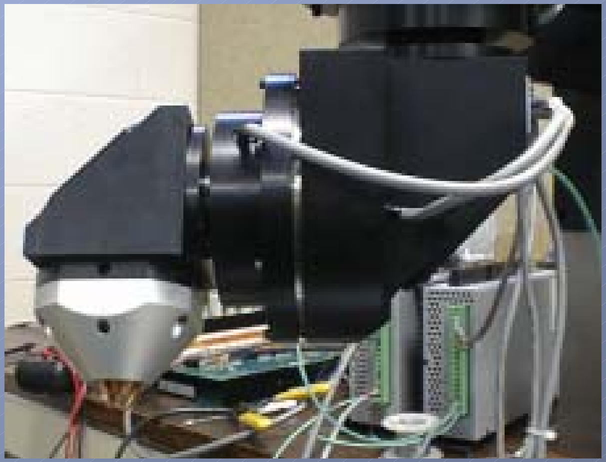
LENS™ Processed
SX 432 Grade Nanocrystalline WC-18 wt.% Co powder

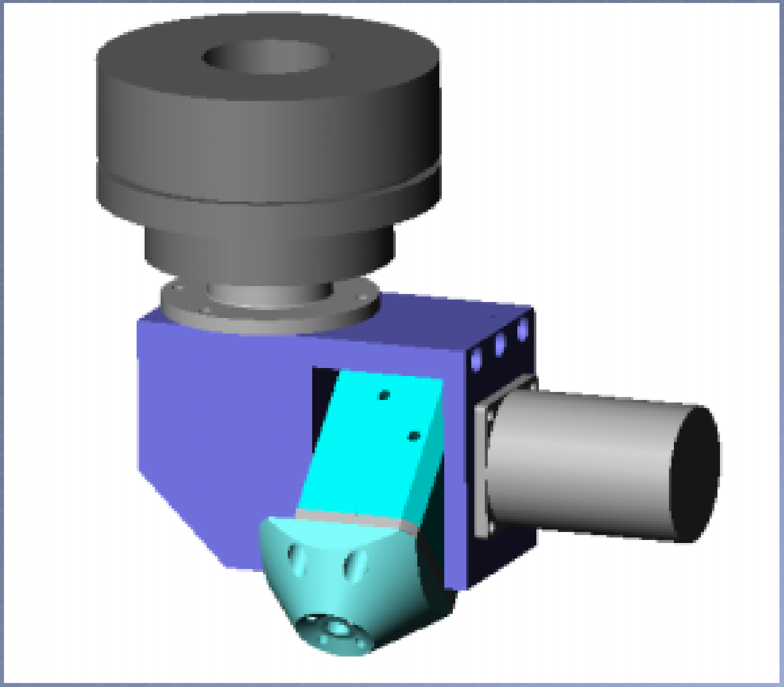


(a) Low magnification **(b) High magnification**

Laser power = 180 W

Laserwrist™ Adds 4th and 5th Axes





Optomec

Sandia National Laboratories

Part is Built with Deposition Head Perpendicular to Vertical

QuickTime™ and a
Intel Indeo® Video R3.2 decompressor
are needed to see this picture.

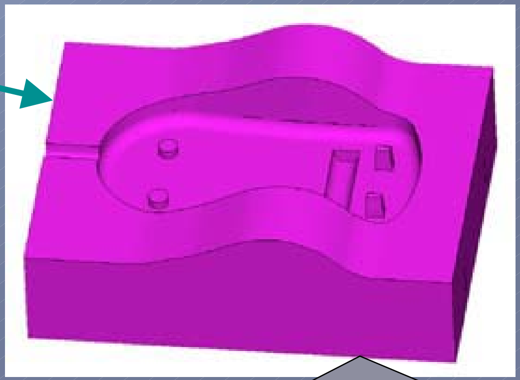
Jack Build

Jackbuildpb

Summary of Model Based Materials Processing (LENS™) for In-Space Materials Fabrication

1. Models and Physical Metallurgy Principles Based Forming Technology
   - No Tooling to Achieve Useful Shaped Functional Objects.
   - Unique Additive Forming Ability for Structural Materials
   - Hollow Internal Features to Reduce Weight
   - Reduces Amount of Starting Material and Need for Machining to Make Parts.
2. Provides Enhancement of Mechanical Properties
   - Via Rapid Solidification and Refinement of the Microstructure
     - Strength Enhancement Without Loss of Ductility.
3. Inherent Capability to Engineer Composition, Microstructure, and Properties Simultaneously While Shaping the Material.
4. Process Improvements Include Higher Build Rates and Greater Overhang Build Capability
5. Could Provide Nearly Universal Materials Procesing Capability

Conformal Cooling Channels: Built Into Tooling During Fabrication



Conformal Cooling Channel